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THE IMP-F&G PRE-BOOST REGULATOR

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ABSTRACT

The Pre-boost Regulator was used as a main bus regulator in the IMP-F and G spacecraft, a continuation of the Interplanetary Monitoring Platform scientific satellites. Two voltage-regulated, current-limited busses, used on the spacecraft for instruments and experiments, define the output of the regulator, while the parallel combination of the solar array, battery, and shunt regulator determines the input characteristics. A series switching regulator operating at 5 kHz and controlled by a simple magnetic amplifier provides a voltage output of 11.7 volts for a majority of the instruments and experiments, while a dc to dc converter operating from the 11.7 v line adds 16.3 volts to it and thereby provides a 28 v bus for the transmitter and other experiments. A current transformer is utilized for load current sensing and is effectively coupled to the magnetic amplifier for current limiting-short circuit protection on both outputs.

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INTRODUCTION

The IMP-F&G spacecrafts were a continuation of the Interplanetary Monitoring Platform series of scientific satellites. Following the design completion of the Prime Converter for the Anchored IMP satellites a request was submitted for the design of a prime converter with higher efficiency and power level capability than previously required. This developed because of increased power demands by the spacecraft experiments and instruments to achieve the IMP-F mission goal.

A requirement imposed on previous prime converters of the IMP satellites was input-output isolation. This particular requirement, coupled with an output voltage level higher than the minimum input voltage resulted in a payment in efficiency of approximately ten percent. In addition, multiple outputs, input voltage transients and load transients also added to the cost in efficiency.

A simple modification on the design of the prime converter used on the anchored IMP was proposed as a solution to the immediate requirements of the power system for IMP-F. Basically, two outputs were to be supplied. One output was to be 11.7 volts, and the other, 28 volts; both common to the input return.

The primary power system for the IMP-F satellite is very similar to the power systems of the previous IMP series. A solar array, shunt regulator, battery and prime voltage regulator supplies the power for the spacecraft electronics. A block diagram of this system is shown in Figure 1.

PRE-BOOST REGULATOR

A block diagram of the prime converter used on A-IMP is shown in Figure 2. The converter consists of a switching regulator, a dc to dc converter, and individual series regulators.[1] The pre-regulator is a closed loop voltage regulator, consisting of switching elements, storage elements and control elements for pulse width modulation. The dc to dc converter utilizes switching elements in a magnetic-coupled oscillator configuration and is synchronized at the same operating frequency of the pre-regulator. Series dissipative type regulators provide the necessary regulation for each line.

The output voltage of the pre-regulator is less than the minimum input. The minimum input is determined by the battery, and for the IMP series is 12 volts.

In the case of the pre-regulator, the output voltage is approximately 11.7 volts. In the past, the main bus for the spacecraft experimenters and instrumentors was 12 volts, and usually the experimenter provided its own voltage levels by dc to dc converters. Thus, it became evident that an output voltage of 11.7 volts instead of 12 volts would be acceptable. The efficiency of the pre-regulator was approximately 92% to 96% over the input voltage range of 20 to 12 volts. This was attractive, compared to an overall efficiency of 76% to 80% of the prime converter.

One main bus at 11.7 volts was not sufficient to satisfy the requirements of all the instrumenters. A higher voltage, 28 volts, was required by the transmitter. The addition of a dc to dc converter operating on the 11.7 volt line and adding 16.3 volts to it, resulted in a secondary output of 28 volts. Thus, the term pre-boost regulator was attached to the main regulator of the primary power system for the IMP-F spacecraft, and a block diagram of it is shown in Figure 3.

PRE-REGULATOR

For the purpose of description, several figures representing various portions of the pre-regulator will be used. To begin with; the primary power handling components function together as indicated in Figure 4. The input filter consists of capacitors C_5, C_6 and inductor L_1. Diode D_{16} prevents the voltage across C_5 from going negative with respect to ground in the event of contact bounce or momentary power application at the input terminals. Switching transistors Q_1 and Q_2 are alternately driven into saturation by a duty-cycle control circuit operating at a constant frequency of approximately 5 kHz. The resulting voltage waveform is averaged by the output filter consisting of L_2 CRI, and C_8.

A two-transformer square wave oscillator operates directly from the regulated 11.7 volt output and thus maintains a constant frequency of operation. This oscillator drives the duty-cycle control circuit shown in Figure 5, synchronizes the dc to dc converter utilized for the 16.3 volt boost and provides drive for a current sensor. Two saturable reactors in a full wave configuration are the control elements of the duty-cycle circuit, and in the particular configuration shown, yield very good drive characteristics for the switching transistors. They are controlled by two separate control windings; one for input voltage-sensing and one for outvoltage sensing. The input voltage sensing winding is in a direction to saturate the cores, thus aiding in obtaining a minimum duty-cycle and also providing a limited "open-loop" control. The output voltage sense winding is connected in a bridge-circuit sensing the output voltage, and thus forms a "closed loop" control. An additional winding shorted through a limiting resistor allows the "active" core to partially reset the "inactive" core each half cycle of operation, and results in a form of system dampening.

Short circuit protection or current limiting is inherent in some type of voltage regulators. Current limiting is evident if voltage drive circuitry is employed to establish a base current for the main regulating transistors. However, the amount of current limiting is unpredictable and sometimes occurs at an unsafe operating level which would result in destruction of the main regulating transistors. Short circuit protection, that is, a circuit which turns itself off in the event of a direct short circuit placed across the output, is inherent in circuits whose drive is directly derived from the output. The pre-regulator as described up to this point exhibits both of the mentioned characteristics. Since the output of the pre-regulator is the main bus of the spacecraft, some form of protection against accidental faults or system protection was needed. With this in mind, additional circuitry was added to the basic pre-regulator to achieve current limiting and short-circuit protection features.

Current limiting in the pre-regulator is achieved by sensing the load current and reducing the duty-cycle of the main switching transistors when the predetermined load current is reached. Current sensing is accomplished by utilizing a current transformer in the configuration shown in Figure 6. The current transformer consists of 1 turn for the primary and 1000 turns for the secondary, wound on a Bobbin tape wound core, and is driven by a "square wave" voltage source, e_1, derived from the oscillator. Neglecting magnetizing current, the current flowing through the main loop, i_1, will be proportional to I_e by 1/1000, is unidirectional, and establishes a dc voltage across R_{17} - C_{17}. Consequently, this voltage will be directly proportional to the load current, I_e. Diodes D_{10} and D_9 allow the load current, I_e to reset the core during the half cycle when diode D_{11} is blocking the source voltage e_1. Since the emitter of Q_8 is connected to the lower leg of the output voltage sensing bridge circuit, the base looks like an open circuit to the RC parallel combination and does not load the current sensor output, E_S, until it exceeds the emitter voltage by the V_{be} of transistor Q_8. As Q_8 becomes conductive, the resulting emitter current tends to override the control current established by the output-voltage sensing bridge, effectively limiting the load current as a result of the lower duty-cycle. As the load resistance is reduced, both the output voltage and load current decrease, until a region is reached where the pre-regulator switches to a different mode of operation. This comes about because power for the duty-cycle generator is derived from the output, and as the output voltage is reduced the frequency of operation reduces, and results in a decreasing duty-cycle. The system then becomes degenerative and the pre-regulator would turn off if the "starting circuit" did not exist.

A starting circuit is required by the pre-regulator to initiate a regenerative build-up of the output voltage. The primary requirement on the starting circuit is that it must supply sufficient power to the duty-cycle generator to drive the switching transistors conductive and to the point where the system becomes regenerative. However, in the event of a short circuit placed on the output of the pre-regulator, the starting circuit should limit the amount of power d livered to the short-circuit and to the duty-cycle generator. The circuit illustrated in Figure 7 meets this requirement. In normal steady-state operation of the pre-regulator, Q_7 is back biased by selecting the zener voltage of D_8 to be less than the output voltage of the pre-regulator. During the transient condition when the pre-regulator is turned on, transistor Q_7 is rendered conductive until the output voltage builds up to the zener-voltage of D_8, and diode D_{16} prevents the load on the pre-regulator from by-passing the available current from Q_7. Thus Q_7 supplies a limited amount of power to the duty cycle generator during the turn-on transient or a short-circuit (low resistance load) placed on the output of the pre-regulator.

PRE-REGULATOR PERFORMANCE

Maximum efficiency of the pre-regulator is reached when the switching transistors are operating at a 100% duty cycle (corresponding to minimum input voltage) and at a power level where both the fixed and series resistive losses are small compared to the output power. At minimum input voltage the losses consist of drive power and I^2R_S where R_S represents the effective series resistance between input and output. As the input voltage increases, additional losses occur, and consist of switching losses (transistors and comutating rectifier) and reactive component losses (input and output filters). Graphical plots representing the measured efficiency as a function of input voltage and output power are shown in Figures 8 and 9.

The input voltage requirement of 12 to 20 volts imposes a large change in duty cycle in order to regulate the output voltage. Consequently, the closed loop gain of the regulator is high, and the regulator exhibits a low output resistance characteristic. Voltage regulation as a function of input voltage and output power are illustrated in Figures 10 and 11. The flat curve of the output voltage vs "input voltage is a result of the combined closed loop and open loop control.

Current limit-short circuit protection characteristics of the regulator are illustrated by the E_0 vs I_0 plots in Figure 12. These curves were obtained by loading the regulator with an active load instead of a resistive load, and consequently the region where the regulator "switches" modes of operation is not clearly shown. However, the region can be identified by calculating the required load resistance for each point on the curve. The regulator does not completely turn off because the starting circuit provides a reduced drive to the switching transistors and the duty-cycle generator is limited to a min. duty cycle. The lower portion of the E_0 vs I_0 curve represents a constant-power curve.

As indicated by the curves of Figure 12, the value of current limit is dependent on input voltage. This characteristic is mainly dependent on the fact that the current transformer primary winding is placed in series with the inductor of the output filter for fabrication simplicity and also to eliminate any noise voltage across the primary from being conducted to the output. As a result, a high input voltage causes a high ac component of current to flow in the inductor, and the current transformer tends to read the peak value of current rather than the average value.

BOOST CONVERTER

The addition of a dc to dc converter to the pre-regulator described completes the requirement of a higher voltage output. A converter similar to that used on the AIMP-D&E prime converter was employed. This converter consists of a magnetic coupled oscillator synchronized by the squarewave oscillator utilized in the duty-cycle generator. The converter is shown schematically in Figure 13.

The converter is synchronized by the square wave voltage appearing between the bases of Q_3 and Q_4. Resistor R_8 limits the available current upon switching so as not to turn the non-conducting transistor on until the conducting transistor is fully off. The magnitude of the synch voltage is designed so as to result in approximately zero current flow during each half cycle, and only a pulse of current during the switching interval. This arrangement results in a phase difference between the two oscillators which is dependent on the storage time of transistors Q_3 and Q_4 and the magnitude of pulse current flow during the switching interval.

A low pass filter, consisting of L_3 and C_{10} isolates the converter input from the pre-regulator output and prevents the resultant ripple at the input of the converter from appearing on the 11.7 volt line. By connecting the secondary center-tap to C_{10} instead of C_8 (pre-regulator output), the ripple voltage appearing across the boost output, C_{11}, is cancelled by the ripple voltage across C_{10}, and the resulting 28 v output is relatively clean.

Since the Boost converter derives its power from the 11.7 volt line, it exhibits current limited short-circuit protection without requiring current sensing. Load current of the boost converter is reflected to the pre-regulator and since the boost converter output voltage is directly proportional to the pre-regulator output voltage, the 28 v bus follows proportionally the pre-regulator E_0 vs I_L characteristic. A plot of the E_0 vs I_L characteristic of the 28 v bus is illustrated in Figure 14 for three input voltages.

OVERALL PERFORMANCE

Overall efficiency, voltage regulation and ripple measurements of the two output lines on the Pre-Boost Regulator are tabulated for reference in Table 1. Photographs of the finished flight unit is shown in Figure 15. Particular wiring techniques required to keep the stray magnetic field level within the limits specified are evident by inspection of the photographs. With the wiring technique followed, an additional compensating loop was required in some cases to reduce the maximum stray level of around 7 gamma at 18 inches down to 4 gamma.

A circuit-breaker feature was utilized in the primary power system of IMP-F&G to automatically disconnect all experiments from the 11.7 v and 28 v line in the event of an overload. The overload was detected by an input-current and voltage measurement approximating an input power and set to trigger when a predetermined safe level was exceeded, or by a short-circuit detector incorporated in the pre-boost regulator. The short-circuit detector was required to cover the region where a low resistance fault in either line would cause the input power to decrease rather than exceed the predetermined safe level as a result of the pre-regulator current limit-short circuit protection features. Both detectors incorporated a fixed time delay to account for transient conditions. Once the circuit breaker is tripped, the fault could be located and removed by ground command.

The short circuit detector incorporated in the pre-boost regulator is shown for reference in the complete schematic diagram, Figure 16. It consists of a complementary output stage, transistors Q_9 and Q_{10}, a Schmitt trigger, transistors $Q_{11A\&B}$, and a time delay circuit, R_{28}, C_{16}, and Q_{12}. Transistor Q_{12} prevents C_{16} from charging as long as the 28 v line is above the zener diode voltage level of D_{15}. If a fault occurs on either the 11.7 line or the 28 v line, sufficient to go into the current limit mode and for a period greater than 800 msec., the voltage across C_{16} will trip the Schmitt trigger and capacitor C_{18} will discharge through Q_9 and D_{13} to an external, circuit-breaker driver.

REMARKS

The IMP-F spacecraft was successfully launched on May 24, 1967 and operated continuously until it entered the earth's atmosphere on May 3, 1969. During this period of time the pre-boost regulator operated continuously, reliably, and well within its required limits.

The IMP-G spacecraft was successfully launched on June 21, 1969 and has been operating continuously to date. Data received from the spacecraft has indicated reliable operation of the pre-boost regulator.

Table 1

Pre-Boost Regulator — Typical Data

Input		11.7 v Bus			28 v Bus			Overall Efficiency In %
Voltage In Volts	Ripple In mv	Voltage In Volts	Load In Watts	Ripple In mv	Voltage In Volts	Load In Watts	Ripple In mv	
20	32	11.70	26.2	240	28.16	18.2	46	89.6
20	—	11.70	19.6	—	28.27	13.0	—	89.5
20	—	11.70	13.1	—	28.39	7.9	—	88.2
20	—	11.70	6.5	—	28.51	3.9	—	83.0
16	26	11.71	26.2	145	28.18	18.3	40	91.3
16	—	11.71	19.6	—	28.30	13.1	—	91.3
16	—	11.71	13.1	—	28.43	7.9	—	90.2
16	—	11.71	6.5	—	28.54	3.9	—	85.7
12	13	11.68	26.2	10	28.14	18.2	38	94.5
12	—	11.70	19.6	—	28.27	13.0	—	94.3
12	—	11.70	13.1	—	28.40	7.9	—	92.9
12	—	11.70	6.5	—	28.51	3.9	—	89.4

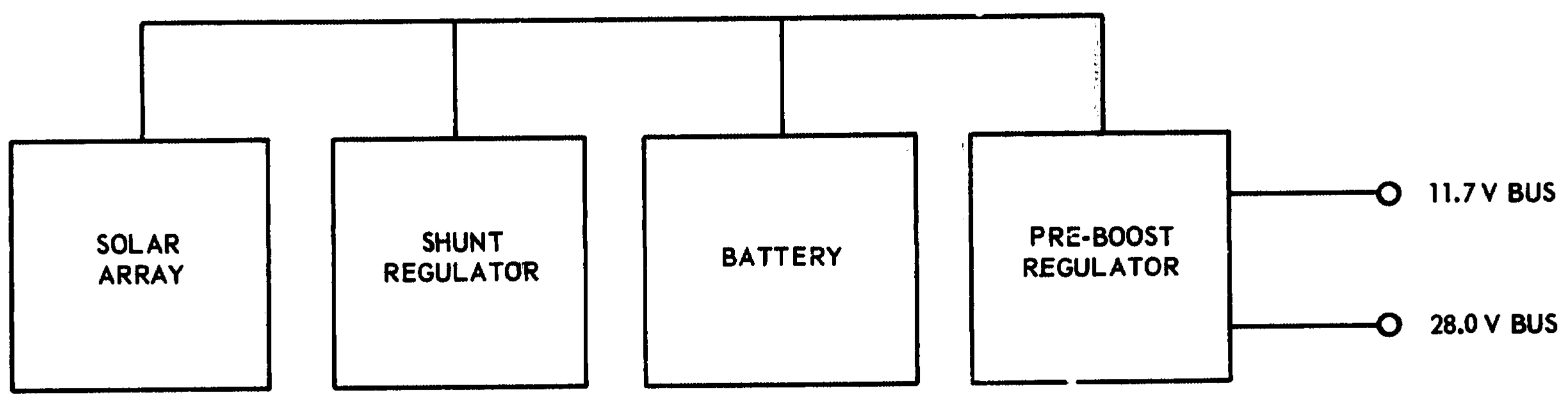

Figure 1. IMP-F&G Primary Power System, Block Diagram

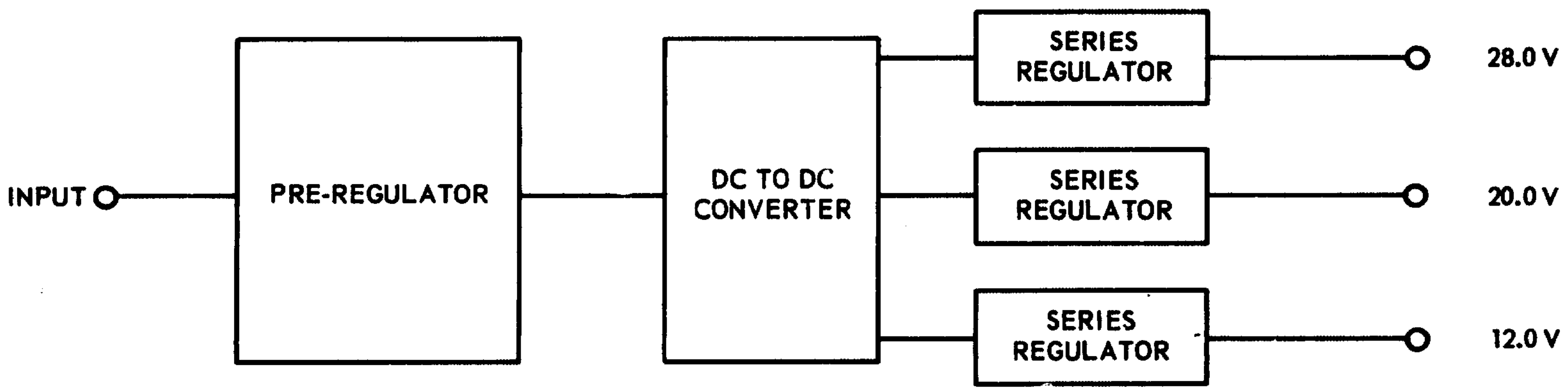

Figure 2. AIMP-D&E Prime Converter, Block Diagram

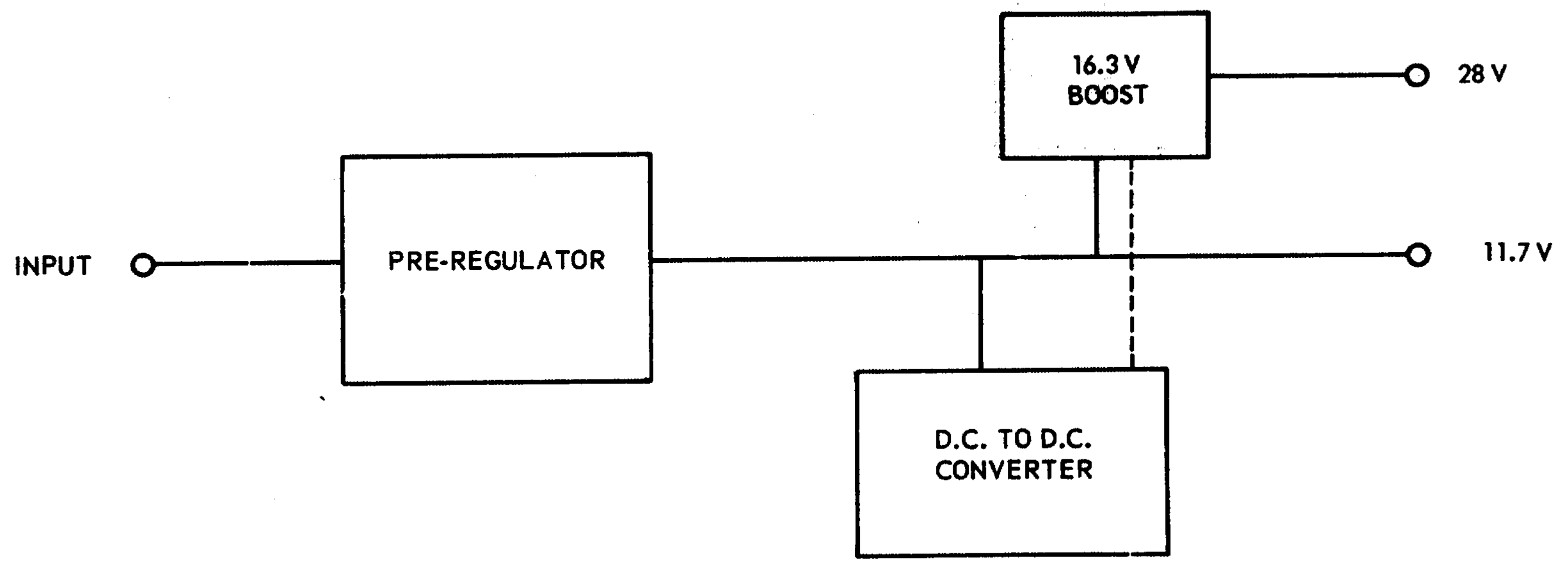

Figure 3. Pre-Boost Regulator, Block Diagram

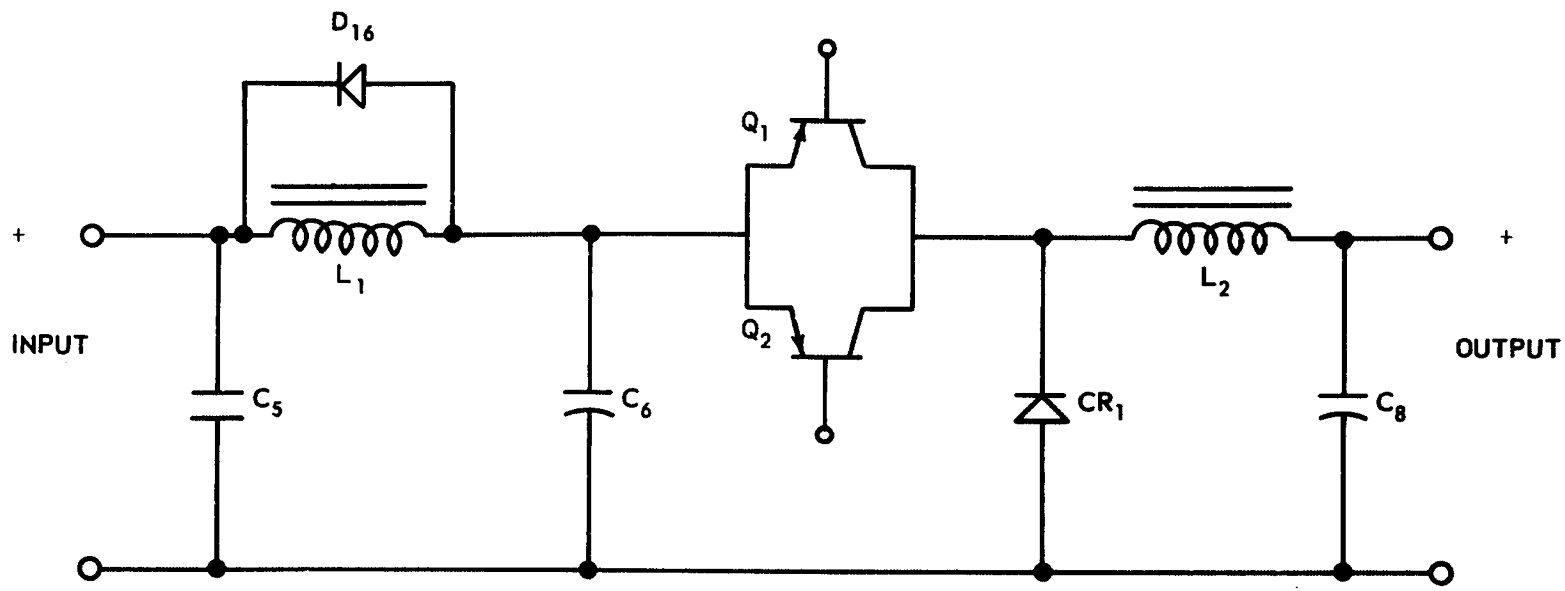

Figure 4. Pre-Regulator, Power Components

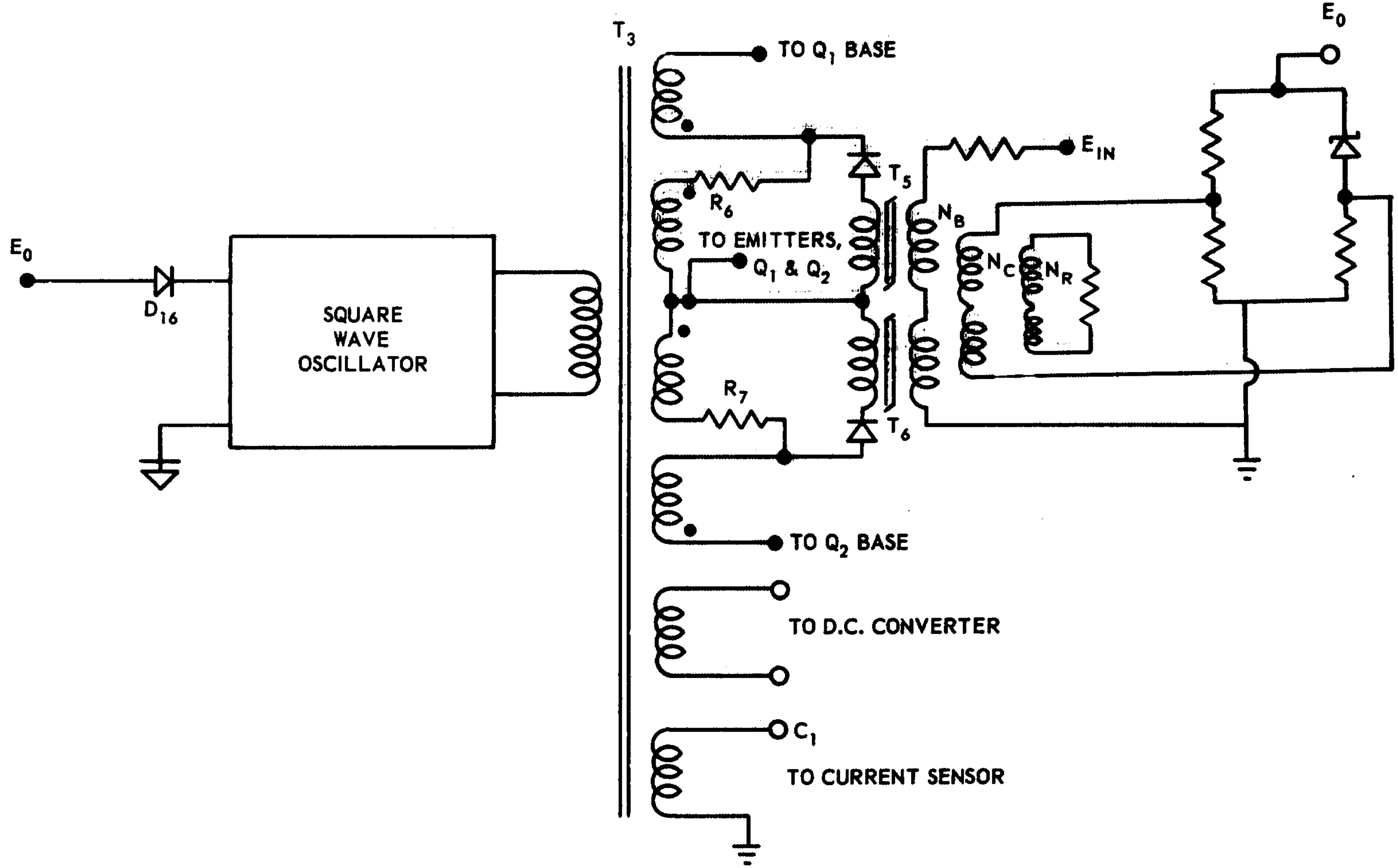

Figure 5. Duty Cycle Control Circuit

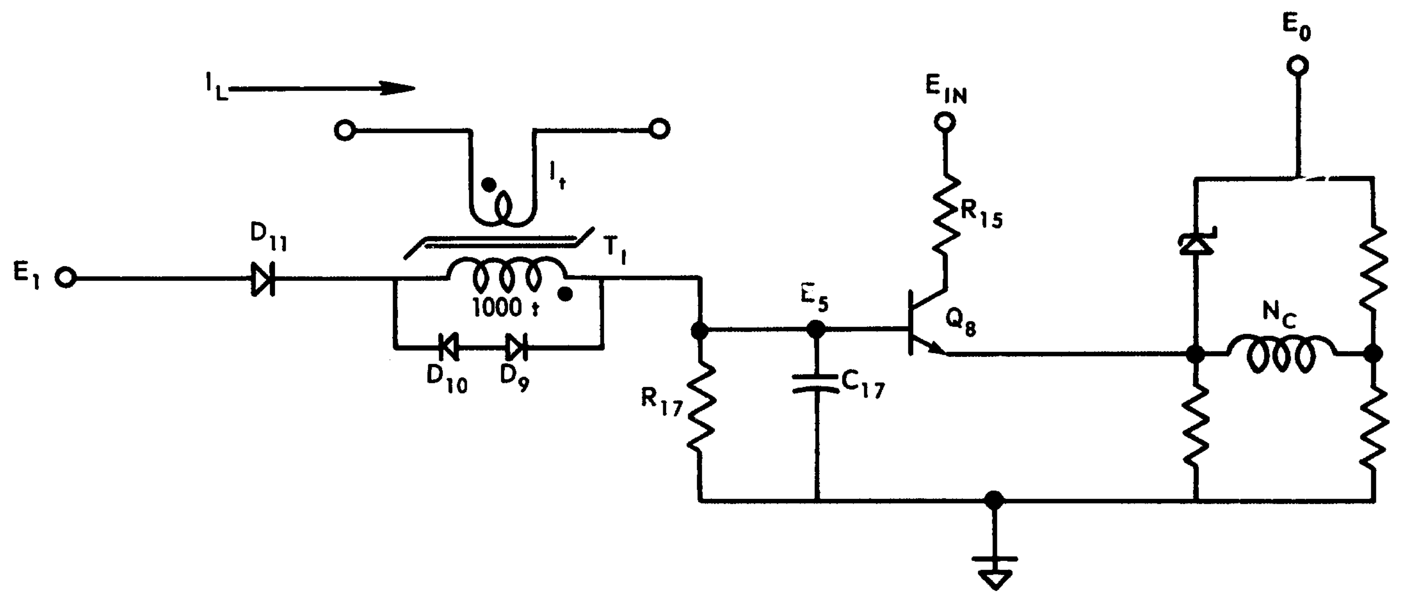

Figure 6. Current Sensor and Limiter

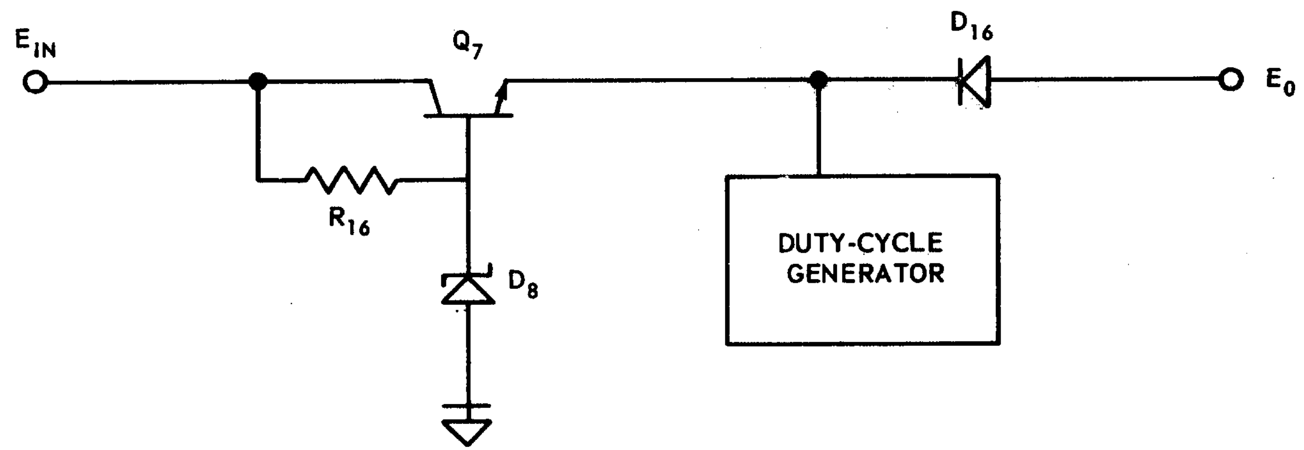

Figure 7. Starting Circuit

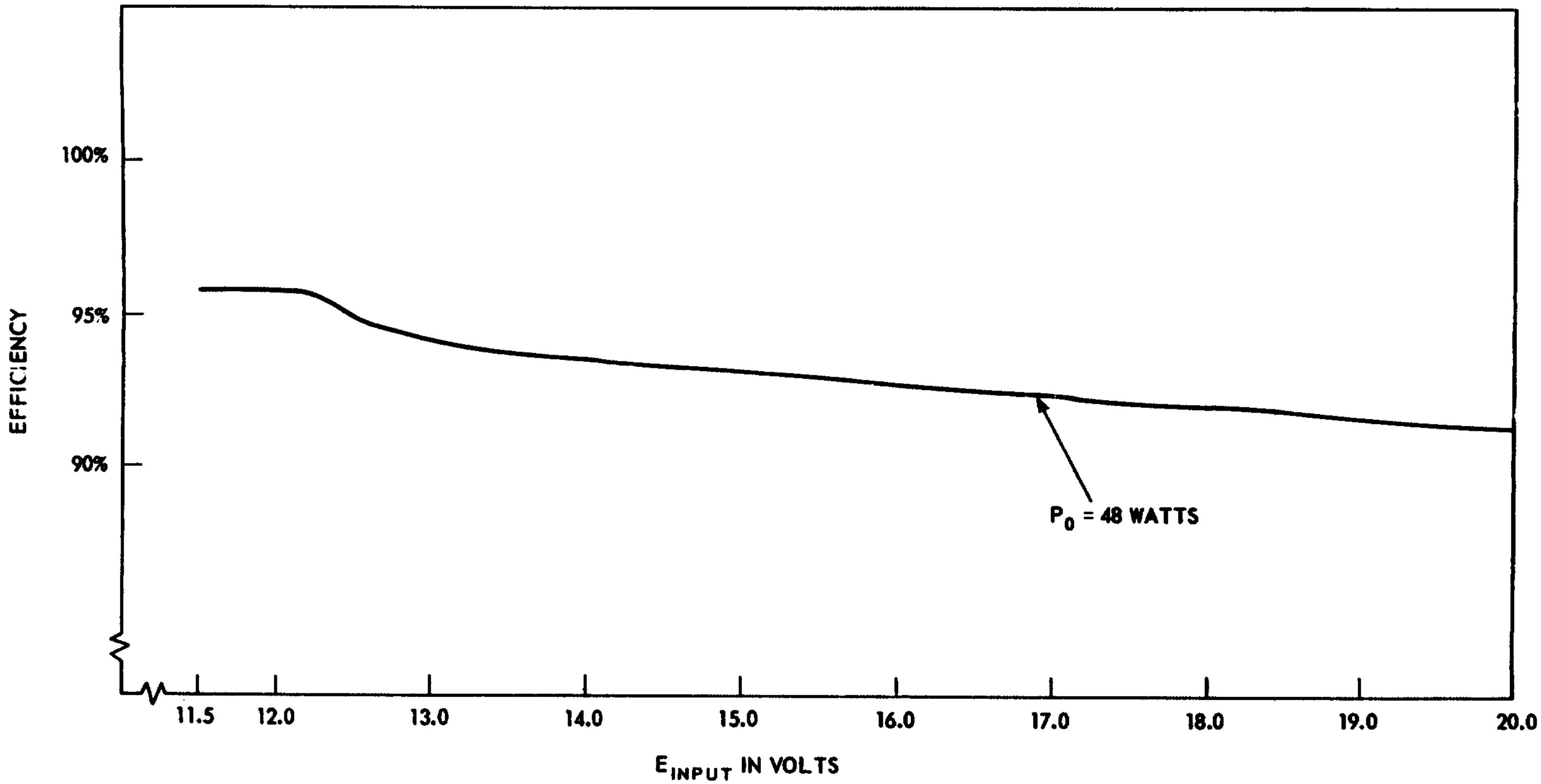

Figure 8. Pre-Regulator Efficiency Vs Input Voltage

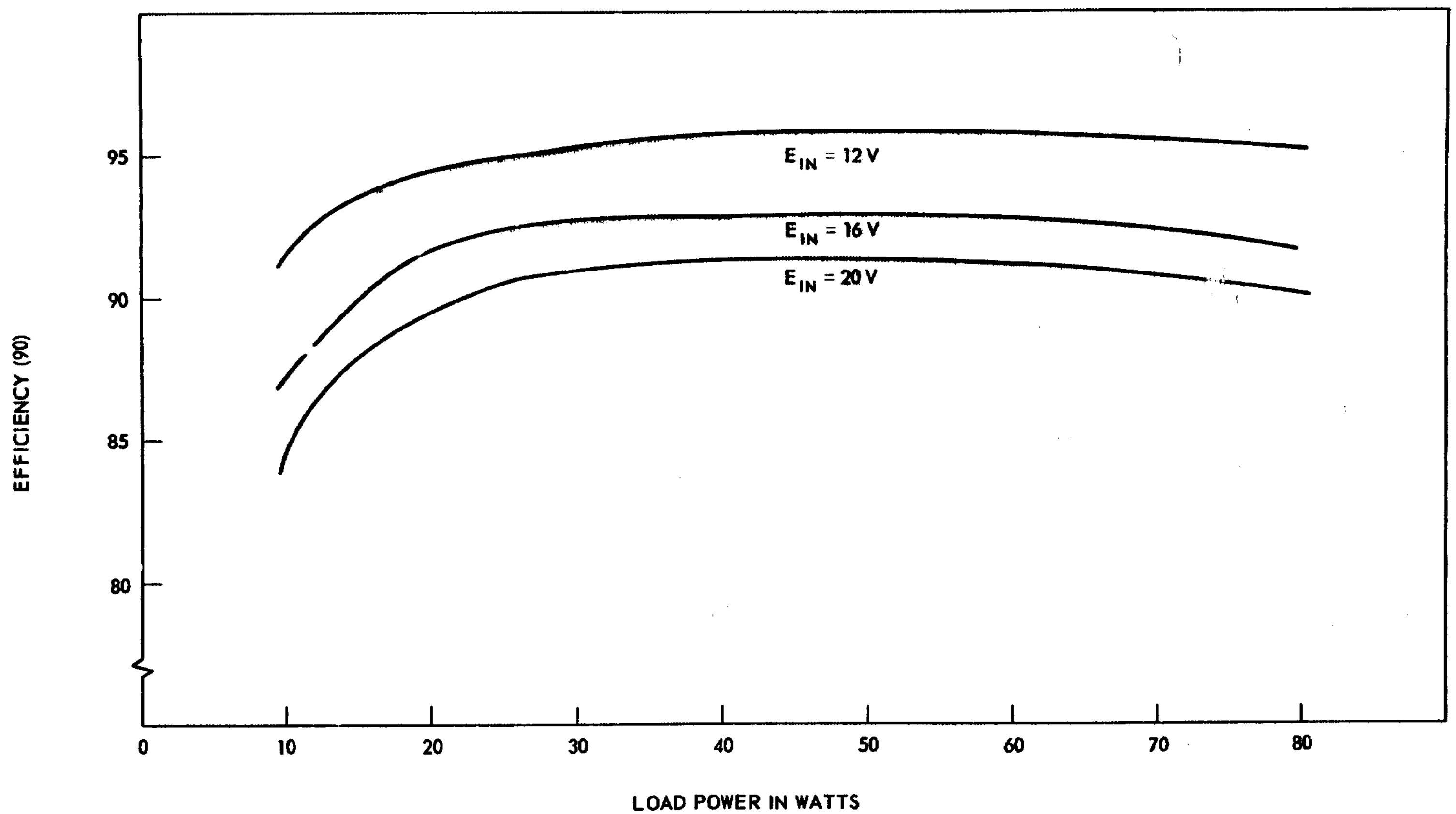

Figure 9. Pre-Regulator Efficiency Vs Load Power

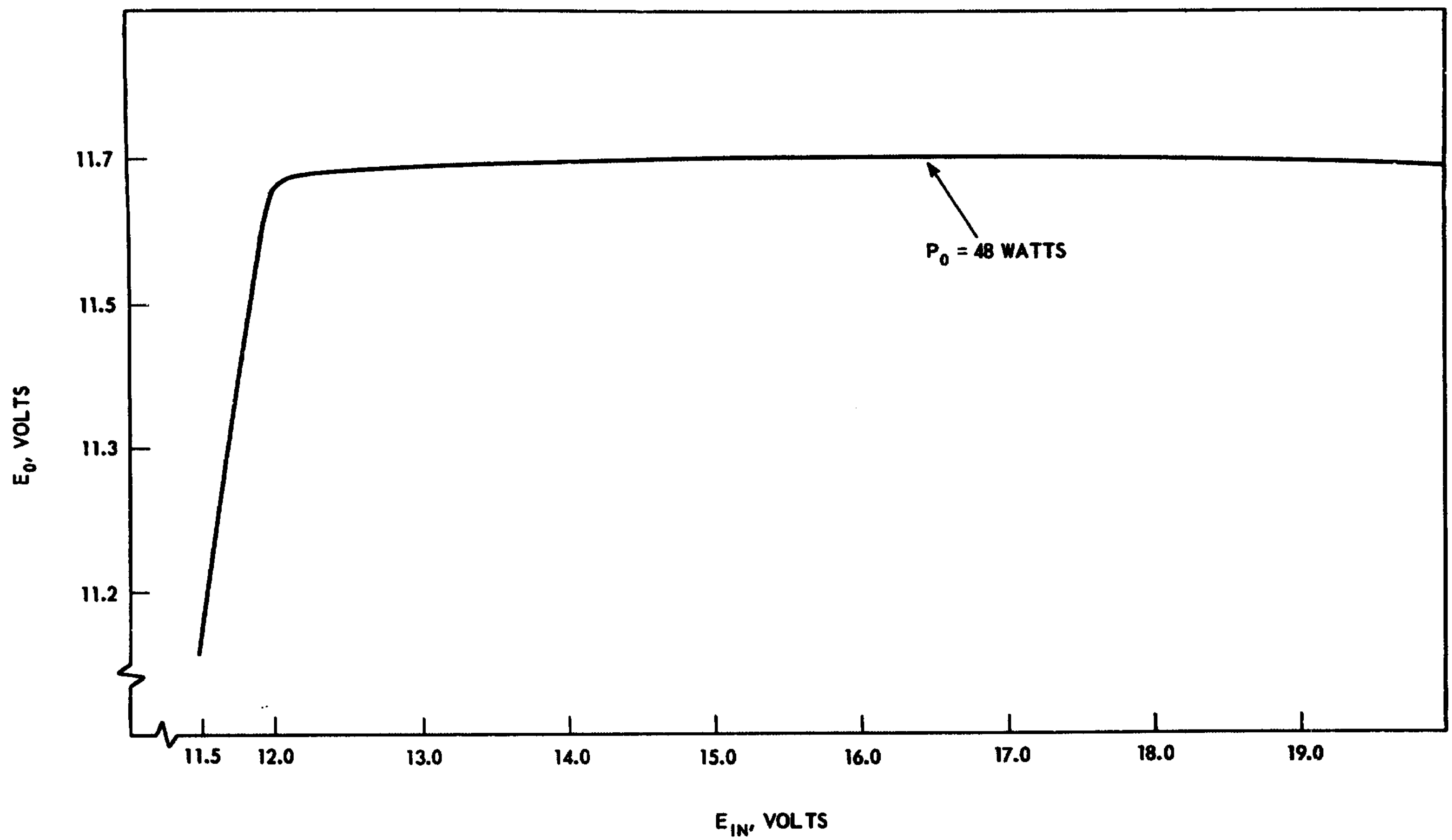

Figure 10. Pre-Regulator Output Voltage Vs Input Voltage

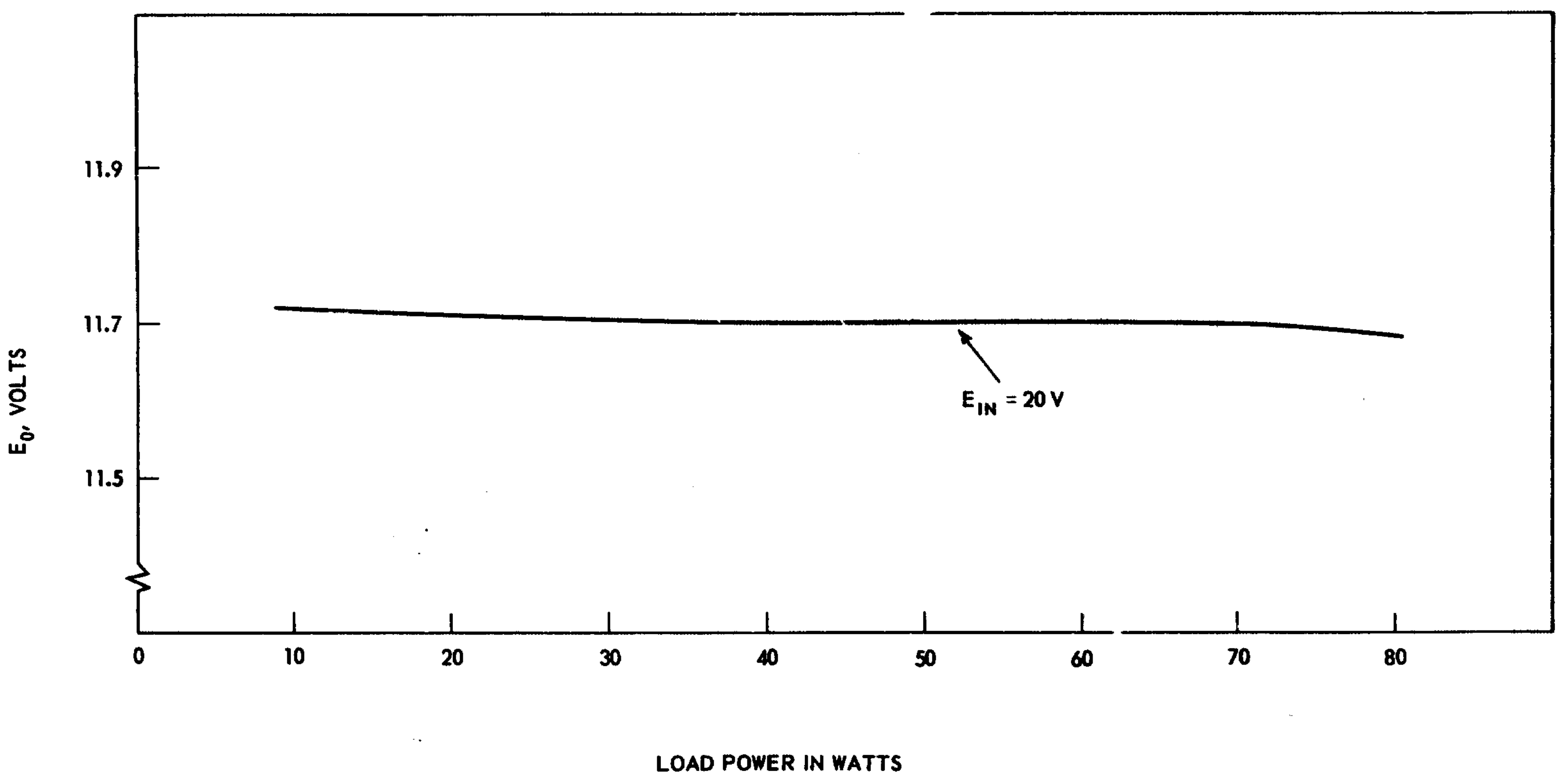

Figure 11. Pre-Regulator Output Voltage Vs Load Power

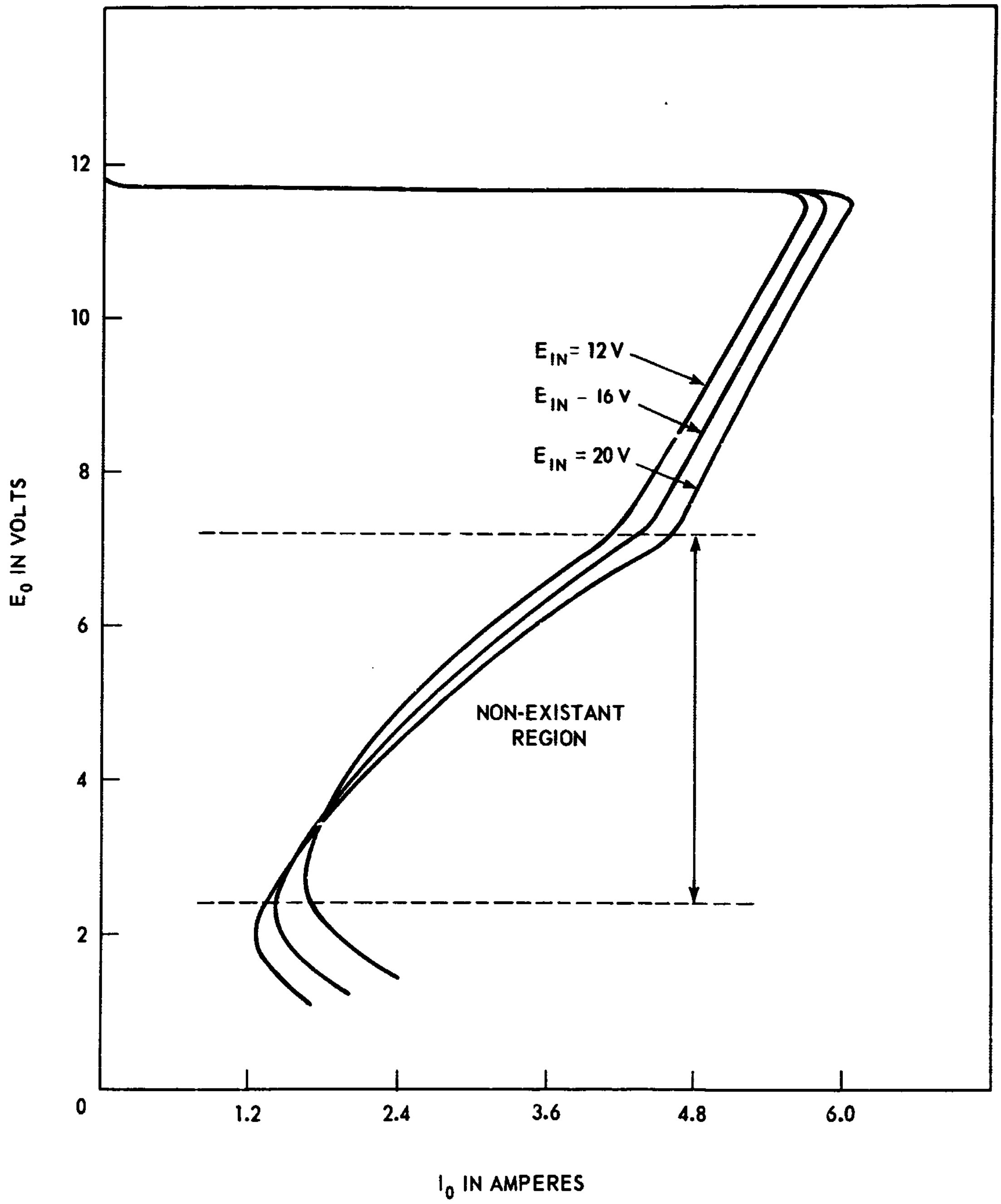

Figure 12. Pre-Regulator Output Voltage Vs Load Current

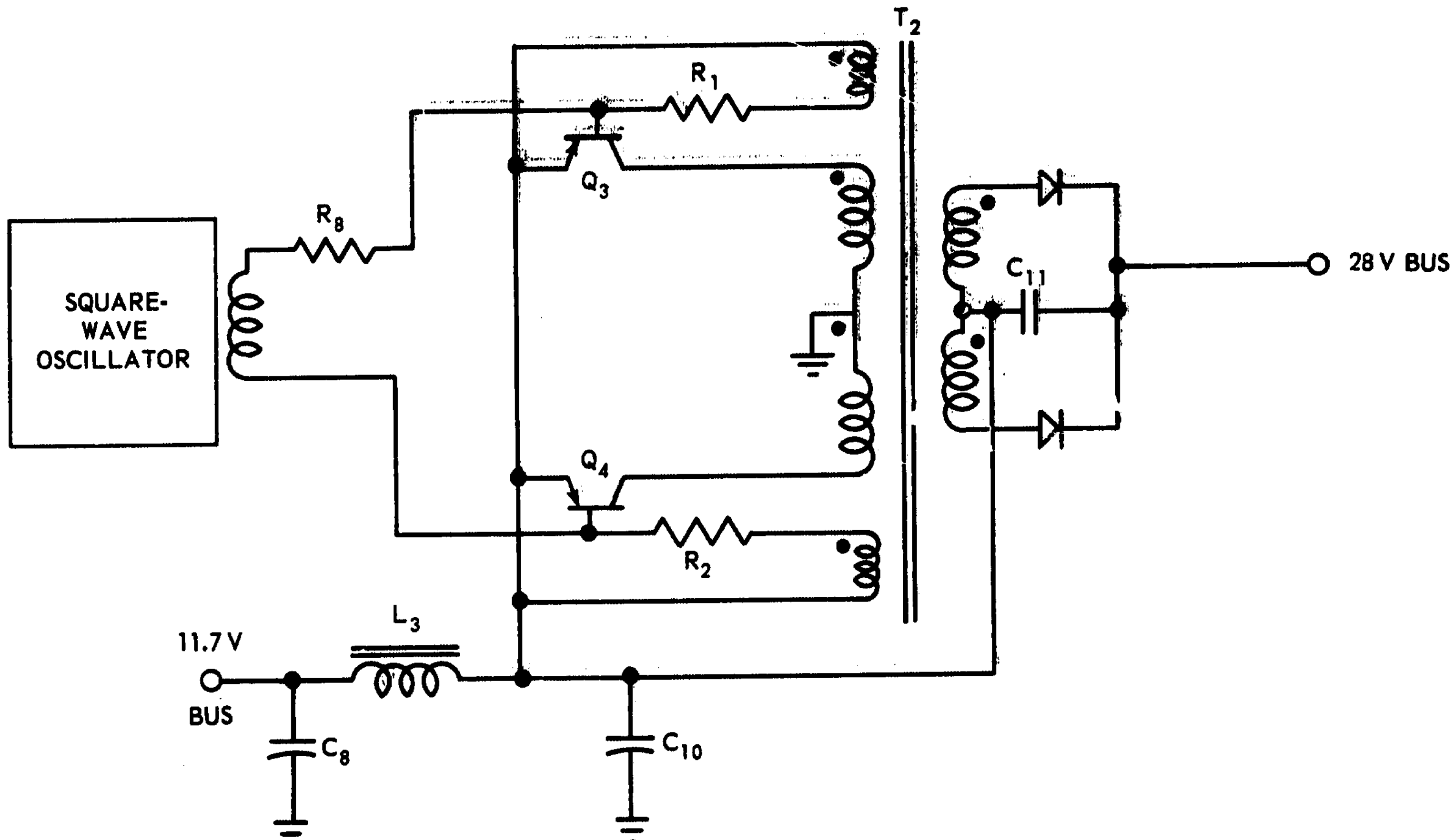

Figure 13. Boost Converter

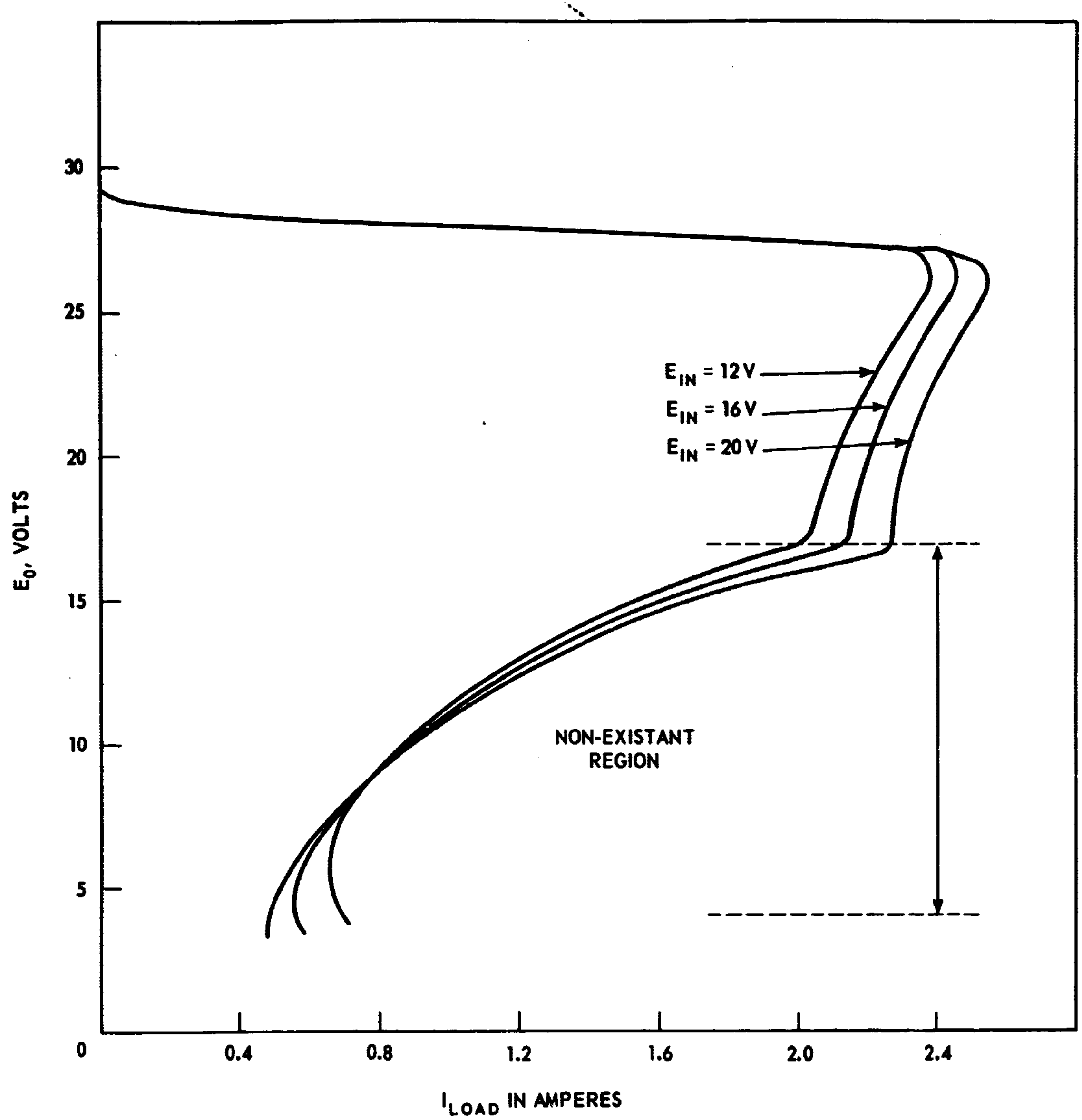

Figure 14. 28 v Bus Voltage Vs Load Current

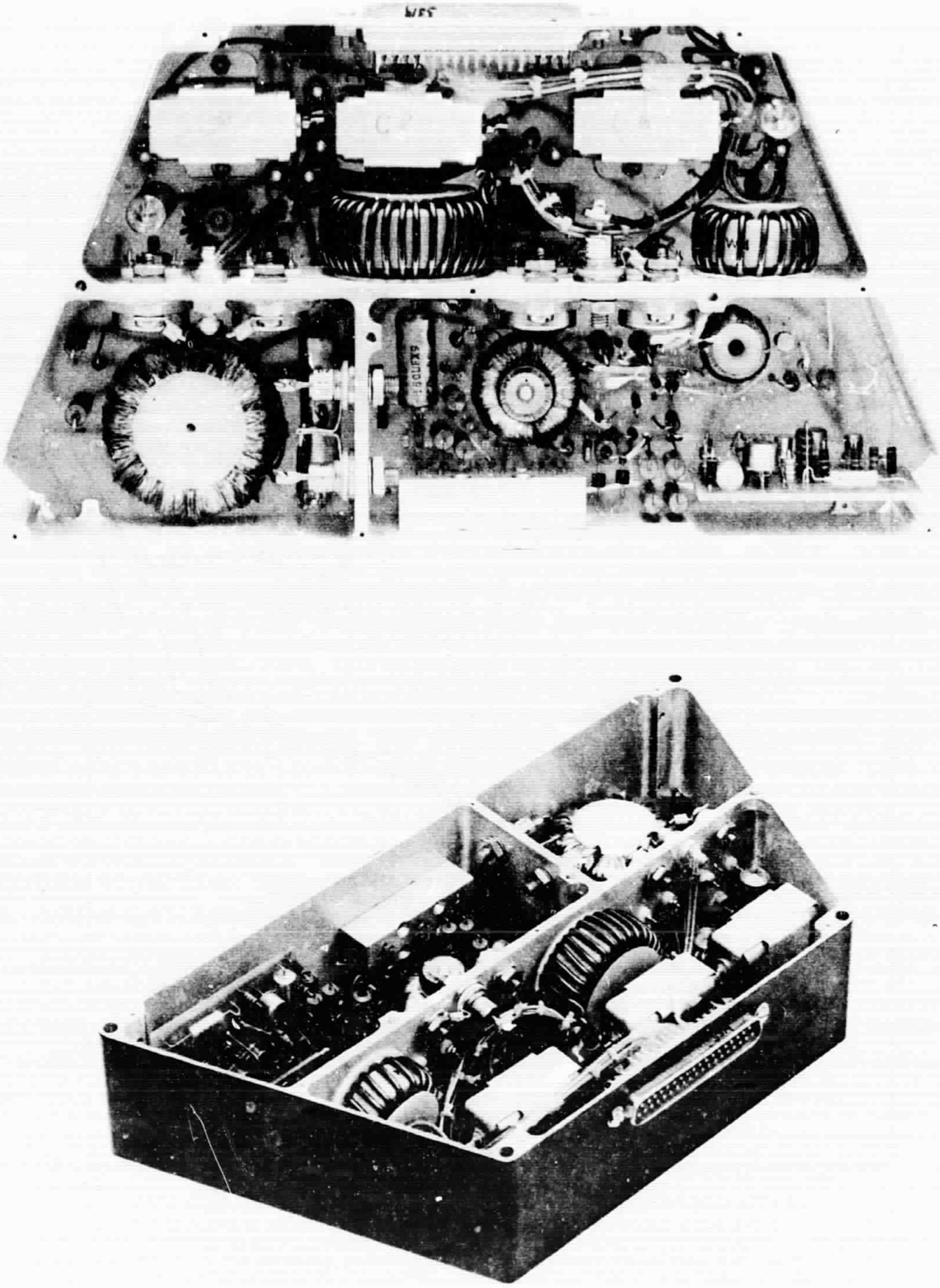

Figure 15. Photographs of Pre-Boost Regulator

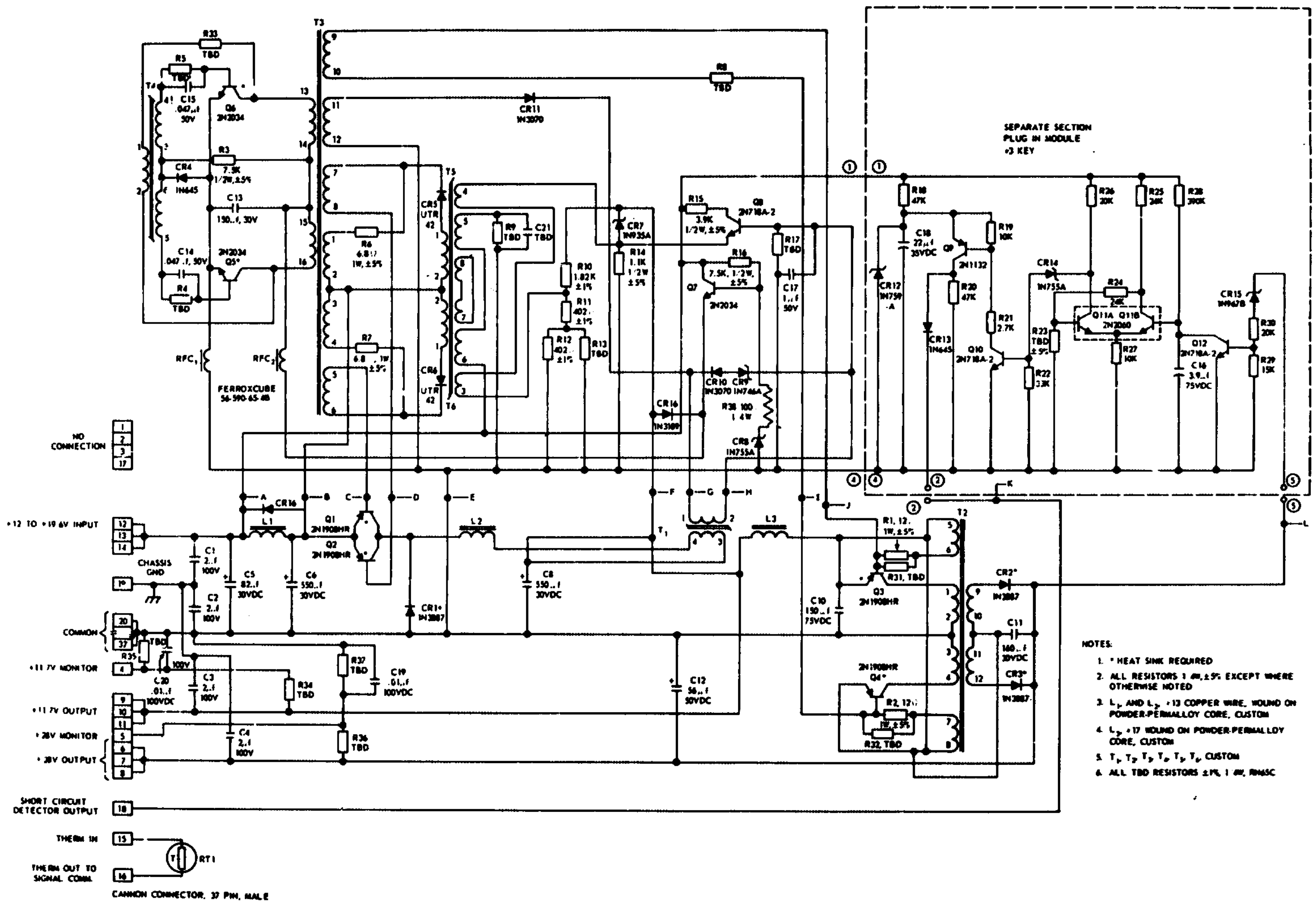

Figure 16. Schematic Diagram of Pre-Boost Regulator